TESTING ULTRASONIC SH WAVES TO ESTIMATE THE QUALITY OF ADHESIVE BONDS IN SMALL HYBRID STRUCTURES

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ABSTRACT: Shear Horizontal Guided Waves (SH-waves), a special type of ultrasonic waves, were used to investigate the applicability for an assembly of aluminium sheet or tube with a polymer structure. For any kind of joining technology, the polymer-metal phase boundary can be considered as a weak point and prone to failure. In order to get information about the structural integrity of the joining, Nondestructive Testing (NDT)-methods are essential. Concerning adhesive joints, some important aspects are not yet accessible by any ready-to-use method: the strength of adhesive bonding, as well as defects like weak boundary layer and "kissing bonds". Surface waves excited in one of the bonded parts exactly interact with this desired region. SH-waves proved beneficial waveform but because of insufficient testing equipment, it has not been possible up to now to examine small structures and samples, e.g. lap joints complying with EN 1465. With state-of-the-art technology, Electromagnetic Acoustic Transducers (EMAT) have been developed to excite the highly pure and short-pulsed waves needed. The study evaluates relevant factors beside a variation in adhesion that can affect the ultrasonic signal in polymer-metal hybrid components in general and lap joints for future tests in particular.

KEYWORDS: Non-destructive testing, ultrasonic wave, adhesive bond, metal-polymer hybrid

1 INTRODUCTION

Lightweight design and functional integration is becoming more and more important for new and advanced products in different industrial areas. Hybrid components play an important role combining different materials and their particular properties to a high-performance system. The study focuses on an assembly of aluminum sheet or tube and a polymer structure. The connection can be established by (a) gluing or (b) direct joining by welding [1, 2] or by injection overmolding processes resulting in direct-adhesion of the polymer and metal phase optionally supported by a primer [3]. Injection overmolding can be considered highly suitable for automotive industry series-production due to low cycle time for complex shaped parts [3, 4]. In order to get information about the integrity of the joining in the real structure, Nondestructive Testing (NDT)-methods are essential. But beyond laboratory setups, only few can fit industrial requirements for in-process measurements. Additionally, there is so far no NDT technique available to ensure the strength of the adhesive bond in multi-material systems [5], allowing only an incomplete assessment of joint quality [6]. In the study presented, a special form of ultrasonic waves has been used to point out its advantages and applicability for laboratory and industrial tasks.

2 NON-DESTRUCTIVE TESTING OF ADHESIVE BONDING

For any kind of joining technology, the polymer-metal phase boundary can be considered as a weak point and prone to failure. Two types of defects can occur: (1) localized defects, e.g. lack of adhesive, void, disbond, kissing bond (zero-volume disbond), etc. and (2) deviation of mechanical properties such as poor curing, porosity and weak adhesion. Lack of adhesive can be commonly detected by active thermography, well-established in automotive and aerospace industry [6]. Various testing techniques are adequate to find defects like pores or debonding [5]. They can be detected because of the phase contrast due to the vacuum or gas phase enclosed. Thus they are also visible with electromagnetic wave based methods, e.g. X-rays. By using the Fokker Bond Tester, disbonds and voids as well as the cohesive properties and strengths can be tested by the analysis of through-thickness vi-

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bration changes since decades [7]. But the quality and strength of adhesive bonding, i.e. the connection between two materials by chemical bonds and intermolecular forces, is not yet accessible by any ready-to-use method [5], just as weak boundary layer and kissing bonds, characterized by edge-to-edge surfaces but with interfacial weakness. Contamination of the adherend's surface is a common source for these defects. They must not be underestimated for fatigue prediction. In addition, diffusion of fluids along these zones is thermodynamically facilitated, degrading adhesion further and weakening the polymer by swelling.

The high potential of adhesive bonding technology is reduced by the inevitable demand for accurate processing conditions and need of extensive process control. This is one reason limiting its application especially in small and medium-sized enterprises. A NDT-method for quality assurance is much asked for.

3 ULTRASONIC SH-WAVES

Shear Horizontal Guided Waves (SH-waves) are a special form of ultrasonic waves propagating in plates. They are characterized by an oscillation of the lattice atoms in the plane parallel to the surface and perpendicular to the direction of propagation. The oscillation happens throughout the whole thickness of the plate, if it is in the dimension of or less the ultrasonic wavelength. This vibration propagates along the plate's length and is reflected at sharp edges, i.e. at the end of the plate.

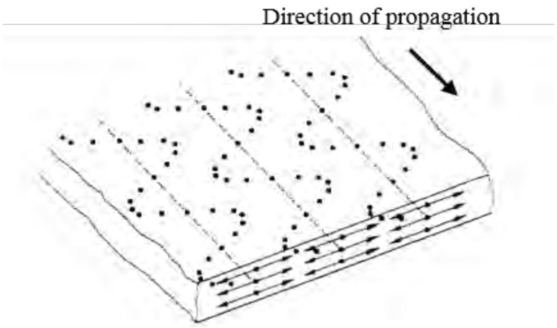


Fig. 1 *Horizontally polarized shear waves (SH-waves) guided through a plate (adapted from [8])*

3.1 PHYSICAL PROPERTIES AND QUALITIES

3.1.1 For evaluation of interfacial adhesion

SH-waves have several advantages [5, 9, 10] and also proved to be promising for application on adhesive bonded samples consisting of two metallic plates [11-16] as well as polymer/composit parts [14, 17]. Because ultrasound is a mechanical wave propagating by displacement of atoms, it is directly linked to the mechanical bondings. Surface waves excited in the bonded parts exactly take effect in the desired region at the adhesive-adherend interface and accumulate information while propagating along the bond. Because of their long-range propagation capability (Fig. 2), waves can be excited apart of the join which can be covered and at inaccessible position. The surface waves at the top and bottom site of a thin sheet are coupled simplifying the excitation throughout the plate and the join.

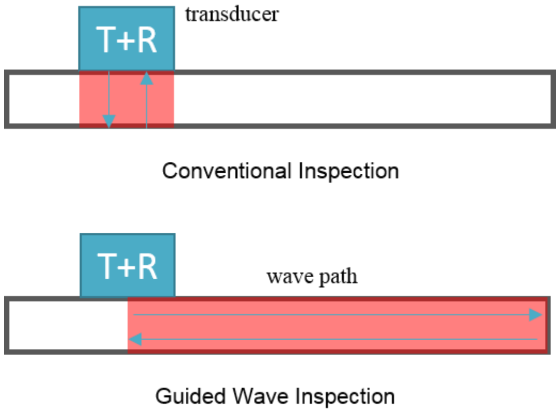


Fig. 2 *Comparison between conventional ultrasonic testing technique and Guided Waves*

The property that particularly emphasizes shear waves, is that adhesive bonded joints are mainly designed for and submitted to shear loads, so shear resistance of the interface is a critical parameter [16]. It has been shown that kissing bonds, when subjected to compressive stress, remain invisible [18]. So Guided Lamb waves, characterized mainly by out of plane oscillation (“Shear Vertical Guided Waves”), in most cases fail to detect these imperfections [18]. In-plane oscillation parallel to the surface, characteristic for SH-waves, is the wave form of choice not only because kissing bonds can be detected theoretically. They are also non-sensitive to liquids on the surface because only adhering solid matter is able to transmit shear forces. A disbond filled with liquid should be detected as well. How SH-waves can be used for the evaluation of interfacial adhesion is part of actual research [14-16, 19].

The study utilizes that the energy loss of the incident wave is highly concentrated in a small area around the interphase between polymer and metal acting sensitive to mechanical boundary conditions. The hypothesis that different extent of adhesion is measureable with the method can be suggested. It was assumed at early times [11, 13] and then confirmed by simulations based on several models [14-17]. But scientific evidence is not yet satisfied as separation of effects is difficult and not yet complete. Comparison with tensile testing and different non-destructive testing methods should be carried out. In a preliminary study presented in chapter 4, ultrasonic testing results had been compared with X-ray tomography what could give an appropriate hint but was also affected by other variables. This study focuses on the variables that occurred and that affect the measured signal on the same way as the quality of the bond.

3.1.2 For robust measurement

The coupling and propagation of guided waves throughout the plate allows variable positions for the transducers. The whole width of the join is interrogated without scanning or even moving of the transducers (Fig. 2).

SH-waves have some physical advantages compared to the nature of Lamb-waves oscillating out of plane: One major problem is, that Lamb-waves are dispersive and that more than one mode exists at any given frequency. Mode conversion can occur at boundaries [20].

The SH_0 wave mode is dispersion free, i.e. the propagation velocity is constant and not influenced by frequency or wall thickness deviations. No mode conversion occurs at the end of the plates. So the shape of the wave packet remains unchanged as it propagates along the structure. The higher wave modes are dispersive but they are not propagable under a threshold value of the product of frequency and wall thickness. For this reason, a mode selection is possible with excitation frequency. To do so, the resulting US wavelength has to be more than twice the wall thickness. This results in signals that are clearly linked to one location of reflection and that contain all information about every energy loss on its way.

3.2 EXCITATION AND MEASUREMENT

The ultrasonic wave form of SH-waves has special requirements for testing equipment. Lamb-waves were popular earlier than SH-waves because excitation was easier and they are till today used more often because of existing testing equipment. They have some disadvantages concerning testing of adhesive bonds mentioned above. However, excitation of SH-waves apart of laboratory setting [12, 14, 17] is difficult with piezoelectric transducers. A piezo element hammering onto the surface cannot move the lattice atoms in a plate directly that way that is needed for in-plane oscillation parallel to the surface. That is the reason why practical SH-wave research advances since the development of Electromagnetic Acoustic Transducers (EMAT). They are suitable for generation and detection of ultrasonic shear waves in metallic and/or ferromagnetic materials. Therefore excitation is only possible in the aluminium plate considering the hybrid samples to be examined. Sound is generated directly in the plate by Lorentz Forces using the combination of small permanent magnets and electric coils driven with a high frequency alternating current. The transducers have been designed as a complementary pair of sender and receiver based on an intensive research and expertise in this area at Fraunhofer Institute for Nondestructive Testing IZFP. We assume insufficient testing equipment available why small structures and samples, e.g. lap joints complying with standards DIN EN 1465 (Determination of tensile lap-shear strength of bonded assemblies) or EN ISO 9664 (Test methods for fatigue properties of structural adhesives in tensile shear), are not examined in actual research. The difficulty with small samples is, that the width of a pulse is high comparing with the amount of time it needs to travel around. The wave propagates in both directions sent off the transmitter along the plate's length. It is then reflected at sharp edges, i.e. at the end of the plate if it has no defects (Fig. 3). Because the acoustic attenuation of the metal is low, the ultrasonic pulses pace around several times. They are reflected again and again at the end of the plate (Fig. 4).

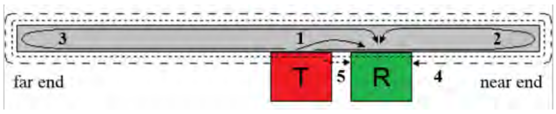


Fig. 3 *Schematic illustration of the propagation of ultrasonic pulses resulting in different signals in time domain*

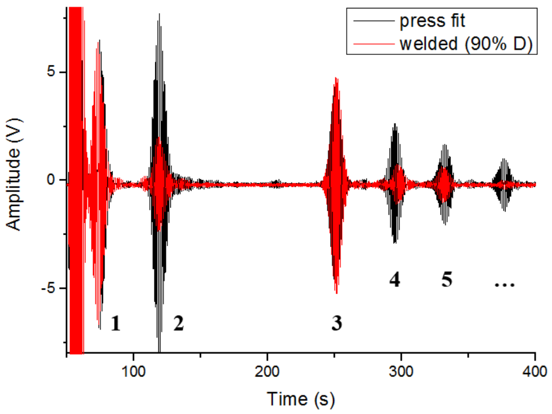


Fig. 4 *Oscillograms of two different joints described in chapter 4: a press fit and a welded joint. Signals according to previous figure. The join is located at the near end. The better join causes a drastic attenuation of signals passing it.*

It is necessary to keep the signals separated to allocate them. Because of the fixed sound velocity, the pulses have to be as small as possible and the distances as large that the first three signals (1) the direct signal from sender to receiver, (2) the one reflected at the near end and (3) the one reflected at the far end of the plate, do not overlap to avoid interference. Then the attenuation of the waves that passed the join can be measured. Narrow ultrasonic pulses need high frequency transmitter driven by an alternating current of the same frequency. They can only be built with the appropriate knowledge of high frequency technology. Transmitters from 200 to 600 kHz are diffused and commercially available. An early work [13] obviously used transducers, which origin cannot be retraced today, with the upper working frequency of 1 MHz in an experimental setup comparable to the favoured. The plates were both steel plates, so beside the Lorentz Forces the magnetostriction could be used for excitation of guided waves. In the experimental configuration, the amplitude was measured through the adhesive joints with transmitter and receiver placed on different plates. In polymer-metal hybrid components, space is much more limited because only one metal part is available to place both transducers upon. It does not seem to be possible up to now to test lap joints of aluminium plates complying with DIN EN 1465 or EN ISO 9664 or small hybrid components. With state-of-the-art technology, equipment to excite the highly pure and short-pulsed waves needed for the samples dimension has been built (results are shown in Fig. 5).

A positive side effect of EMATs has not been mentioned yet: excitation is contact-less and couplant-free, facilitating industrial use.

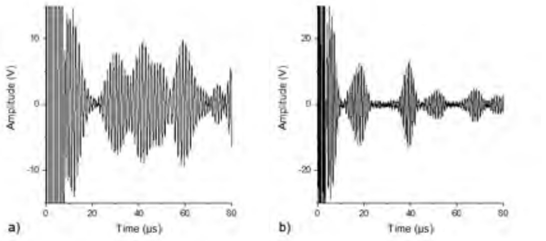


Fig. 5 *Comparison between a) 800 kHz Transducer: signals overlapping and interfering on an aluminium structure of 110 mm length, b) 1 MHz Transducer: clearly separated signals even on a structure of 100 mm length*

4 PRELIMINARY EXPERIMENTS

A preliminary study has been conducted with aluminium tubes of diameter about 10 mm, wall-thickness about 0.5 mm and length about 400 mm. The aluminium tubes have been joined with a polymeric connector (diameter and length 15 mm) at several ways:

- applying force obtaining a press fit
- solvent welding with acetone
- add an adhesive layer on the tube
- welding (radial force applied to get different shrinkage of the polymer onto the tube)

The polymer part was made by rapid prototyping. Another tube was embedded in a two component reactive polyurethane system prevented from flowing into the tube. The results are summarized here. Fig. 4 shows the oscillogram of two different joints. Only the amplitude of the first three signals will be plotted for further comparison (Fig. 6). You can see that the direct signal transmitter to receiver (1) and the echo from the far end of the tube (3) are similar from top to bottom. The signal (2) from the end where the join is located, shows a peak size that drastically decreases. The signal to noise ratio even in case of the lower signals is very high. Looking at the very different kind of joins, the order is logically comprehensible and the results correspond to X-ray tomography carried out for 6 of the samples. The signals are certainly caused by the different join qualities of the samples but it could not be reduced to adhesion because dimension of the joint area could not kept constant, e.g. in case of welding, and the nature of the interface shows a huge difference (Fig. 7). The signals were highly influenced by tilt of the transducer on the curved surface of the tube which has been tried to suppress here and by the reflecting end of the tube. The latter is visible especially in signal (3) where the tube has been slightly deformed during joining process. This can affect results at the join as well, looking at Fig. 7a.

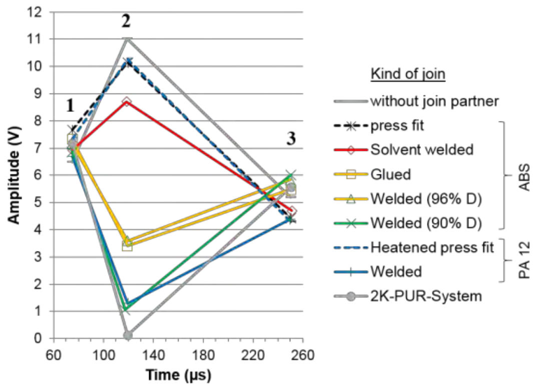


Fig. 6 *The first three Guided wave signals measured on samples with different kinds of join*

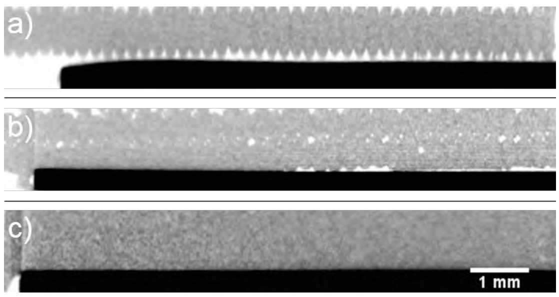


Fig. 7 *X-ray tomography of the aluminium-polymer interface of a) press fit, b) solvent welding and c) welding. The polymer part shown was made by Fused Deposition Modelling.*

5 EXPERIMENTAL SETUP

The experiments were carried out on aluminum sheets of 25 mm width and 150 mm length produced by waterjet cutting. Plate thickness was 1 mm and 1.5 mm. Commercial two component epoxy casting resin was used for embedding one end of the sheets. Immersion depth ranged from 1.5 to 14.5 mm. The polymer part was also varied in size and weight by changing the filling level keeping the immersion depth equal. The shape of the polymer part was given by the mixing cup and almost cylindrical.

Fig. 8 *Aluminum sheet embedded in epoxy resin at one end*

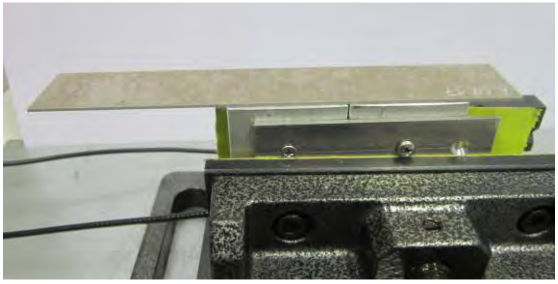


Fig. 9 *Measurement setup of a sheet without a join partner, 800 kHz transducers*

Size of aluminum sheets was based on international standard DIN EN 1465 and EN ISO 9664. Length has been chosen 150 mm to conduct testing with two different EMAT transducers and compare results. Existing EMAT transducers of 4 mm track wavelength (800 kHz) and newly built up ones of 3 mm track wavelength (1 MHz) were used. Only 1 MHz transducers proved appropriate for the length of 100 mm complying with the standard (Fig. 5). Samples can be placed onto the transducers because of their proportions. Sheets were pressed onto the transmitter and receiver which are designed as a pair with fixed spacing. The distance to the free end of the sheet was kept constant.

6 RESULTS

Results are expressed as amplitude of the signal contemplated divided by the amplitude of the direct signal transmitter to receiver. It is denoted as normalized amplitude and a degree of attenuation on the wave path and damping of the join.

6.1 INFLUENCE OF SAMPLE AND MEASUREMENT

Repeatability of measurements is very good (Fig. 10 et seq.). Three plates have been machined at the face side to evaluate the influence of face surface. Waterjet cutting left the surface rough cut. It was then grinded at three different grades. The measurements did not show a relationship. For 1 MHz transducers all results laid in the standard deviation for repeatability of measurements. For 800 kHz transducers the results were scattered in a window up to three times the standard deviation. An influence of the contact force between sheet and transducers couldn't be found either. Contact force was varied with weights from 0.8 kg to 3.0 kg applied onto the same area. However, holding the samples with fingers, applied pressure has a distinct influence probably because of increasing damping area in contact. This can be eliminated by having a metallic connector between fingers and sample, which is anyway needed to avoid influence of electric capacity of human skin.

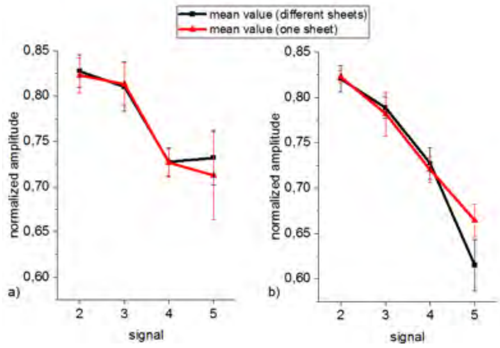


Fig. 10 *800 kHz transducers: Mean value and standard deviation for measurements of five different sheets (black) and the same sheet measured five times (red)*
a) 1 mm sheets b) 1.5 mm sheets

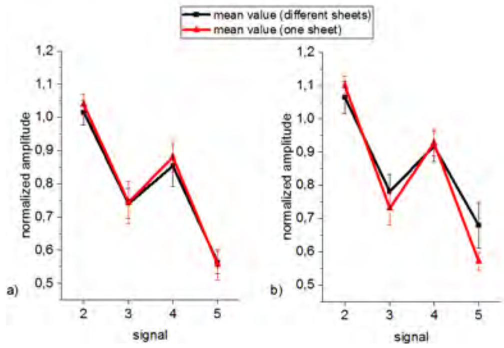


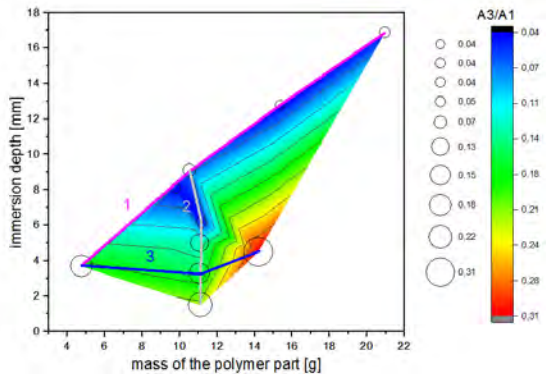
Fig. 11 *1 MHz transducers: Mean value and standard deviation for measurements of five different sheets (black) and the same sheet measured five times (red)*
a) 1 mm sheets b) 1.5 mm sheets

6.2 INFLUENCE OF JOIN DIMENSIONS

Join dimensions were varied in size of the epoxy part and immersion depth of the aluminum sheet. Line (1) indicates the maximum immersion depth that can be realised with an amount of epoxy determined by the size of the mixing cup. Looking at this line, one could already state there is a clear empirical correlation between the size of the joint area and the damping of the ultrasonic signal. But taking into account that the weight of the join changes in the same way, another explanation is also possible. The study clearly illustrates that the mass of the polymer part adhered has a big influence onto measured signal in this experimental setup. Realising samples with equal weight and different immersion depth leads to an apparently linear relationship between joint area and ultrasonic signal. Error bars resemble the respective standard deviation taken out of Fig. 10 or Fig. 11. The confidence interval of the 800 kHz transducers is much better than the one of the newly built 1 MHz transducers but the results are reproduced nevertheless (Fig. 13, Fig. 15).

1 mm sheets:

a)



b)

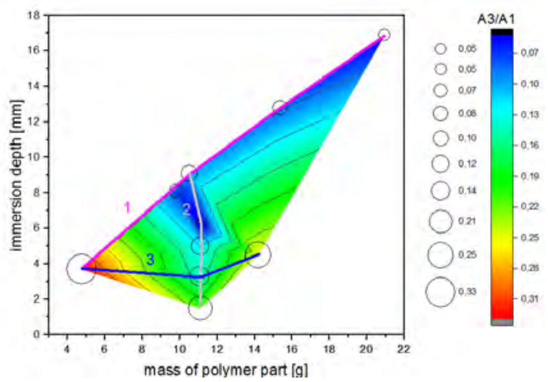
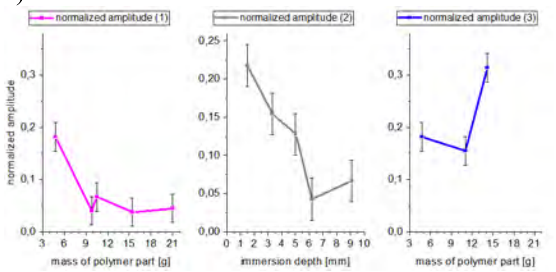


Fig. 12 *Signal received from the join: Normalized amplitudes (A3/A1) of 1 mm sheets measured with a) 800 kHz, b) 1 MHz transducers*

a)



b)

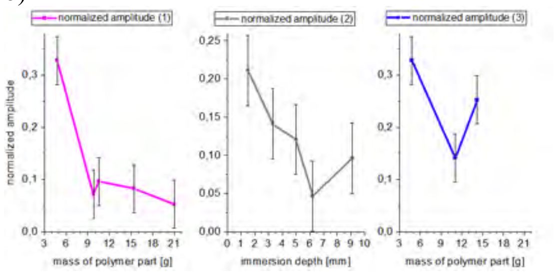
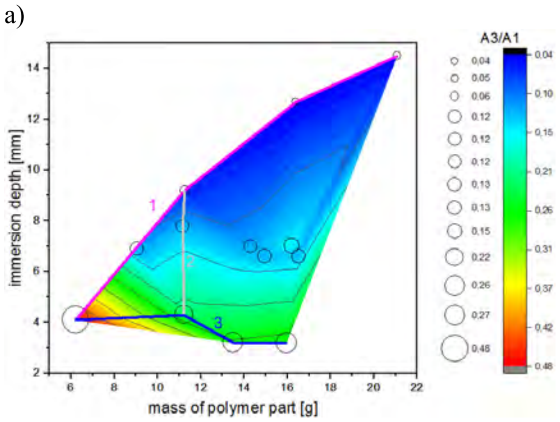


Fig. 13 *Illustration of measurements along indicated lines a) 800 kHz, b) 1 MHz transducers.*

1.5 mm sheets:

a)



b)

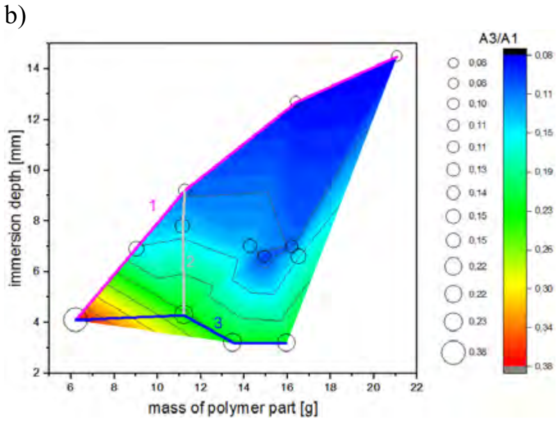


Fig. 14 *Signal received from the join: Normalized amplitudes (A3/A1) of 1.5 mm sheets measured with a) 800 kHz, b) 1 MHz transducers*

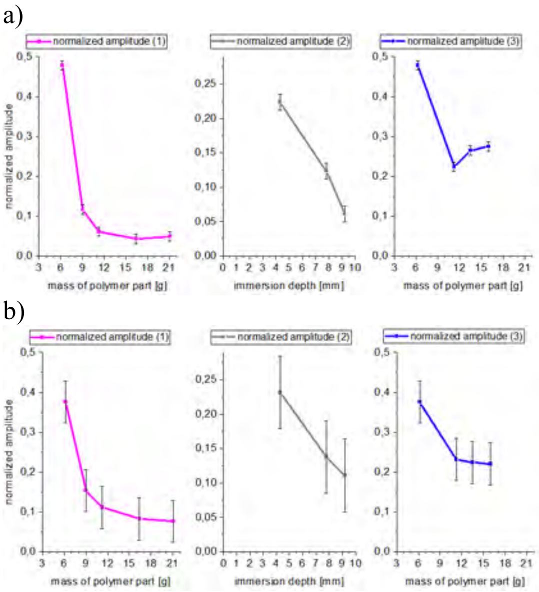


Fig. 15 *Illustration of measurements along indicated lines a) 800 kHz, b) 1 MHz transducers*

7 CONCLUSION

The study evaluated relevant factors beside a variation in adhesion that can affect the ultrasonic signal detected from adhesive joints. Samples of aluminum sheets immersed in epoxy resin at one end were used. Different relationships between joint area and ultrasonic signal could be found. They all correspond to reports in the literature that the quality of an adhesive bond can be determined by the attenuation of guided wave signal as the ultrasound-based method mechanically interrogates the bond. A comparable measurement of a joint made of one metallic sheet and a polymer has not been published before. Results confirm that the extent of the adhesive-adherend interface can be measured. Realising samples with equal weight and different immersion depth leads to an apparently linear relationship between joint area and ultrasonic signal. A high potential to detect disbonds and lack of adhesive can be concluded. The study illustrates that the mass of the polymer part adhered has also a big influence onto measured signal in this experimental setup, where sample size is comparatively small. An explanation could be given by a) the oscillating mass induced by the vibrations of the metal sheet and affecting ultrasonic attenuation or b) emerging of leaky waves propagating in the polymer.
The measurements did not show a relationship between face surface roughness and reflected ultrasonic signal. Nevertheless, an influence of the reflecting edge was distinct in a preliminary study. Conclusion can be given that not the roughness but the shape of the edge is crucial. The influence of surface roughness of the bonding area has not been investigated yet. Surface treatment and roughness plays an important role considering adhesion of polymer and metal [3]. The results have to be taken into account if a study of lap joints between a metal sheet and a polymer or composite part should be realised.
For the study, a combination of physically pure wave excitation and smallest transducers known was used. SH-waves, the guided waveform used, proved beneficial for adhesive bond inspection and also have several advantages for industrial use: The application is easy and the measurement time is very low compared to other testing procedures. Even at this point of research, an in process IO/NIO classification is worth to be examined.

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